Summary Preliminary T962 ODH Analysis

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(1.0) Introduction

This document summarizes the preliminary ODH calculations. The purpose of this document is to determine if it is feasible for the Minos Hall to be ODH 0 if a 500L liquid argon dewar is used for the T962 experiment.

(2.0) Consequence of Large Rapid Argon Spill

What if there were a large sudden argon spill directly onto the floor of the Minos Hall? Assume the worse possible failure with no ODH precautions taken. The argon is either liquid or very cold vapor that has not mixed with air. The argon will spread across the floor and flow into the water drainage gutters below the floor level of the Minos Hall. The water drainage gutters would most likely carry argon into the Minos access hall, escape tunnel, and elevator area. The pit below the elevator has the lowest elevation and a large quantity of argon could collect in it.

The escape tunnel is well ventilated. Although no calculations have been made, it seems likely that the ventilation in the escape tunnel will keep it safe from oxygen deficiency hazards. However, if there is a power outage and the diesel generator did not start, there would be then an oxygen deficiency hazard in the escape tunnel and elevators.

The volumes of the rooms involved and the amount of argon available are displayed in Table 1.

Table 1

Volume Of Minos Hall	172,000 cubic feet
Volume of Minos Access Tunnel	92,000 cubic feet
Total Cavern Volume	264,000 cubic feet
Volume of Total Argon Inventory ***(at 1 atmosphere and 70 F)***	8900 cubic feet
Volume of 5.1% of Argon Inventory ***(at 1 atmosphere and 70 F)***	450 cubic feet

Table 1 shows the volume of the Minos Hall and Minos Access Tunnel and the their sum called the total cavern volume. These volumes were calculated using dimensions from *NuMI Tunnels and Halls #6-7-4*. The actual as-built volumes are larger because of the tunneling methods left arched not flat ceilings and rounded not square corners. The forth row shows the volume filled if 560 L of liquid argon were unpressurized and warmed to room temperature. The meaning of the fifth row is discussed in Section 7.0.

Consider the oxygen concentration resulting from such a spill. Assume there is no ventilation and the argon displaces pure air out of the hall as it is spilled. The following table 1 shows the resulting oxygen concentration and fatality factor for different degrees of mixing of argon with air. The calculations for table 1 assumed 560 L of liquid argon were spilled. The maximum argon inventory is one 500L argon dewar with one 160 L dewar connected to it for filling operations.

The fatality factor, as defined by FESHM 5064 is the fractional probability (a number from 0 to 1) of a person dieing in that atmosphere. A fatality factor of 1 implies certain death; a 0 fatality factor implies no chance of death and a fatality of 0.25, for instance, implies a 25% chance of death.

Table 2

case	*Extent Of Mixing*	*% O2*	*Fatality Factor*
1	complete: floor to ceiling	20.29%	0.0 fatalities
2	bottom 7 ft from floor mixed	18.24 %	0.0 fatalities
3	bottom 3 ft from floor mixed	14.56 %	0.0000378 fatalities
4	bottom 1 ft from floor mixed	1.69%	1.0 fatalities

Oxygen concentration and fatality factors in Minos high bay and access tunnel for spill of total argon inventory, with no ventilation. Each row of table displays a different case, each with a different degree of mixing with air. The listed O2 concentration is in the zone of mixing. For example, in case 4, the zone of mixing is within 1 ft above the floor, above 1 ft height the O2 concentration remains 21% and below 1 ft, the O2 concentration is 1.69%. The calculations are found in reference 2, sections 3.2-3.4.

Consider the case 4 in Table 1. If a person was working at floor level, perhaps working on the wiring on the bottom of a relay rack, or if a person fell to floor while fleeing, that person will likely die. However, in case 4, if a person were standing the whole time, their head would be in a 21% oxygen atmosphere.

For each of the 4 cases, If a person were standing on the floor, they are always guaranteed at least a 14.5% oxygen atmosphere to breath. If a person climbs to an elevation 7 ft or higher above the floor they are in a completely safe atmosphere, at least from the ODH point of view.

The degree of mixing of argon and air cannot predicated. However by looking at the range of possibilities displayed in Table 1, some conclusions can be drawn about the possible hazards.
If a person is laying down, or falls or is even sitting there is a great hazard and a high possibility of dying. The chances of survival greatly increase for a person standing on the Minos hall floor. Better than 99.9% of the people who are standing should survive. Anyone who climbs to a height of 7 ft or more will survive.

There are several lessons that can be drawn from this what-if that are useful for the ODH analysis:

(1) The ODH analysis should assume a fatality factor of 1 (implying certain death) for an unmixed argon spill on the floor of the Minos hall.

(2) liquid argon or unmixed argon gas cannot be spilled directly onto the floor. There must be some type of open topped tank or container that will collect spilled argon. There must be a special ODH ventilation system that mixes the spilled argon with air.

(3) Cases 1 and 2 of Table 1 show there is a sufficient quantity of air in the Minos hall and access tunnel for a mixing system to work. Fresh air does not need to be drawn from the surface for ODH emergencies. It is acceptable for the ODH mixing system to draw air from the ceiling of the Minos Hall.

(3.0) Cryogenic System

There will be a 500 L liquid argon dewar. This dewar inner vessel has a flanged connection inside the vacuum jacket with a metal to metal seal. The vacuum dewar jacket also has a large flange. Both the dewar and its vacuum jacket have relief valves. The vacuum jacket will be design to act as containment if the inner vessel. If the inner vessel fails and leaks argon into the vacuum jacket, the vacuum vessel relief valve will vent argon into the vent header. The flanged joint on the vacuum vessel will have an o-ring seal and will leak.

For the preliminary ODH analysis, the argon system outside of the dewar was assumed to have 20 valves, 100 ft of pipe or tube, 100 welds 5 relief valves and 5 joints with metal to metal seals.

(4.0) Vent Header

The vent header is a pipe which will carry the discharge of argon relief valves and vent valves. For example if there is a loss of vacuum in the dewar then there will be a large heat load on the dewar and the dewar main relief valve will open, discharging argon into the vent header. The vent header will also receive discharge of argon from manual or automatic valves used to purge the system or control pressure when the cryocooler is not running. Calculations in reference 2 show that the vent header can be 1 1/2" or 2" pipe. The vent header can be stainless steel or type K copper.

One of the conclusions of this document is, if feasible, to route this vent header to the atmosphere on the surface. Another option considered is to discharge directed into the exhaust of the mixing fan.

There are inherent ODH problems with discharging the vent header into the mixing system. Any operational problems will then cause the release of argon into the Minos hall. The ODH analysis then must not only take into account equipment failure such as cracked welds or leaking valves, but also the consequence of mistakes made, and problems in the operation of the cryogenic system.

Methods of running the vent header to the surface have been considered. It has been recently learned that there is a large ~8" carbon steel pipe that runs in the elevator shaft to the surface. This pipe is not on the drawings. It was used during construction to pump water out from the tunnel. The pipe is visible from below and is capped with a large valve. In the Assembly Hall on the surface it is covered with the concrete floor, but Dave Puska knows the approximate location of the top end. If this pipe can be used, it will be. Since the pipe is carbon steel, the argon that enters it will have to be -20F or warmer. If need be, a commercially purchased (a finned tube heat exchanger with no electricity or moving parts) could be used to warm up the argon before reaching the carbon steel pipe.

If this carbon steel pipe is not usable, then we could install a 2 " pipe in the elevator shaft. The supports in the shaft for already existing water pipes and duct works can the used to support the new vent pipe. The shaft has crane and movable platform from which pipe fitters can install the vertical run of pipe.

(5.0) Mixing System

The mixing system will consist of two parts, a container to catch the spilled argon and a fan and duct work for mix air with the argon. The mixing system must ensure that the Oxygen concentration of the argon/air mixture is 18% or greater.

One plan is to have a stainless steel or aluminum container that looks somewhat like a large bathtub or an empty above ground swimming pool. This container would be underneath the dewar and cryogenic system. The sides would be 2 or 3 feet high and the diameter large enough to catch any argon that is released from the dewar and cryogenic system. This is a simple concept, but the implementation might not straight forward because of the area around the dewar will be very crowded and space is at a premium. The basic plan is still feasible.

Another possibility for the containment is to enclose the cryocooler , argon filter and associated piping and valves in a 24" or 36" ventilation duct. The piping going to the dewar could also be contained in a flexible metal hose. The dewar would have its own open topped container which would be more of a jacket than a bath tub. All of these containers would drain through ductwork, any spilled argon into a lower container where the argon would be mixed with air.

The calculations assumed a 1000 cfm mixing fan. It is large enough to generate 18% O2 concentration for any sustained spill rate of argon. The motor on the 1000 cfm fan could be 1/4 horsepower or less. The fan can be placed on a UPS.

(6.0) Catastrophic Dewar Inner Vessel Failure

If the dewar inner vessel fails then it will leak liquid argon into the vacuum vessel. The liquid in the vacuum vessel will quickly vaporize. The vacuum vessel will be pressurized and the vacuum vessel relief valve will open discharging argon into the vent header. The heat load on the inner vessel will increase, raising the pressure in the inner vessel. The inner vessel relief valve will open, discharging argon into the vent header. The vacuum vessel has and o-ring sealed flange. When the o-ring gets cold, it could crack and leak. Leakage through the vacuum jacket flange will be trapped and mixed by the mixing system.

The calculated leak rate through the vacuum jacketed flange is 147 cfm. The calculation assumed the o-ring wasn't even between the flanges, and there was a 0.010" uniform gap between the flanges. In reality the o-ring, though broken and cracked will still impede the argon leak. The calculated 147 cfm rate is very conservative. It doesn't just assume the o-ring is broken; it assumes the o-ring doesn't exist. But still the 1000 cfm mixing fan has sufficient capacity to mix enough air into a 147 cfm argon leak to get an 18% oxygen concentration

The probability of both the dewar inner vessel and vacuum jacket simultaneously failing is so small it wasn't even entered into the calculations.

(7.0) Catastrophic Piping System Failure

The phrase "piping system", here refers to the top flange on the dewar and everything else except the the dewar. With one possible small exception (that will be ignored here), a thin long 1/8" outside diameter tube attached near the bottom of the inner vessel for argon level measurement all piping connections will be to the top or "vapor side" of the dewar. Any piping leak will be releasing argon vapor not argon liquid.
Assume for the sake of argument, the bolts on the dewar top flange were loosen while the dewar was at its maximum allowable working pressure of 30 psig. There would initially be a high leak rate of argon into the mixing system. The mixing system may even be overwhelmed and the mixture of argon and air exiting the mixing system may have an oxygen concentration less than 18%.

This sounds bad. However, because of the thermodynamics of a two phase fluid, as vapor is boiled off from the dewar, the pressure (and temperature) of the liquid argon will decrease. When the dewar pressure reaches 0 psig only about 5% of the liquid will have vaporized. Once the dewar is fully unpressurized, the leak rate of argon vapor will dramatically decrease. Row 5 of Table 1 shows that at most 450 standard cubic feet of argon gas will be released into the Minos Hall at this initial high flow rate. This volume of argon is minuscule compared to the volume of the Minos Hall.

The boil-off rate of the remaining the liquid argon is due entirely to the heat transfer rate to the liquid argon. There are two possible sources of heat, the heat load through the vacuum jacket and a possible dewar heater used to control dewar pressure and to empty the dewar. The calculations assumed a 4.7 cfm argon release rate caused by the dewar heater (capable of emptying the dewar in one day). The a loss of vacuum accident generates a 7.3 cfm argon leak rate.

To keep with the pessimistic character of this scenario assume the dewar heater is operating at maximum capacity and at the same time the dewar insulating vacuum space has been filled with air. The argon release rate would then be 12.0 cfm. This will be mixed with a 1000 cfm stream of air from the mixing fan. The argon would be well mixed and no ODH problems would occur.

(8.0) Calculation Results

Calculations were performed for three options, numbered 1,2,3 in the order the calculations were done (not in the order of preference). The order of preference is option 2 followed by option 1. Option 3 is interesting, but should not be considered.

Option (1) has a mixing system with two fans in parallel with a UPS. The mixing fans will be on generator backup power as well. Only one fan is needed for the mixing system to work. The vent header discharges into the mixing system.

Option (2) has a mixing system with one fan on generator backup power but no UPS. The vent header discharges to the atmosphere on the surface.

Option (3) has a mixing system with one fan and no UPS. The mixing fan will be on generator backup power. The vent header discharges into the mixing system.

There is a is subtle requirement for options 1 and 3 to work. The calculations assumed there was only a 560 liquid liters of argon brought into the hall. With options 1 and 3, If there is an argon leak we can't just keep bringing an unlimited number of 160L dewars into the Minos Hall without taking some precautions.

The results of the ODH calculations are shown in Table 3 below. Options 1 and 3 have the vent pipe discharching into the mixing system and are therefore affected by the frequency of operational problems. The calculations assumed a major operational problem every 6 months. An operational problem is here defined as an equipment failure or malfunction, or operator mistake that caused a large release of argon (~25% or more of inventory) in a short period of time (~2 days or less).

Table 3

OPTION	*Phi*	*ODH Classification*
1	2.32×10^{-11} fatalities/hr	0
2	1.09×10^{-9} fatalities/hr	0
3	7.55×10^{-8} fatalities/hr	0

Results of Minos Hall ODH calculations for three options assuming there is a major operational problem every 6 months.

As can be seen in Table 3, all options produce an ODH 0 classification. However option 3 is disturbingly close to ODH class 1. The cutoff limit for ODH Class 0 is 10^(-7).

A Next in Table 4 shows the results of repeating calculations except increasing the frequency of major operational is by a factor of 10. Assume one major operational problem every 0.6 months, or about once every two weeks.

Table 4

OPTION	*Phi*	*ODH Classification*
1	2.08×10^{-10} fatalities/hr	0
2	1.09×10^{-9} fatalities/hr	0
3	6.86×10^{-7} fatalities/hr	1

Results of Minos Hall ODH calculations for three options assuming there is a major operational problem every 0.6 months.

In Table 4, only option 3 is ODH class 1. The other two options are ODH Class 0.

(9.0) Other Options Considered

One option considered was to install the vent header so that it discharges into the intake duct of 4000 cfm fan EF4 which draws air from the ceiling of the Minos Hall to the surface. The fan EF4 is also on diesel backup power. Calculations showed that this option would work very well. But it has the same problem as option 3, if there is a power outage and the diesel generator does not start then any argon discharged from the vent header will descend out of EF4 intake duct onto the floor.

Another possible option is to have the discharge of the mixing fan go into vent header that would then go outside. The problem here is how to keep argon from leaking backwards from the vent header through the fan into the Minos hall, if the fan isn't running. The louvers that come come with ventilation fans will not seal well enough.

(10.0) Conclusions

The recommendation is use to option 2 which involves running a vent header to the surface. If option 2 is not feasible because of the expense, then option 1 is very viable. A discussion follows from least favored to most favored.

The safety of Option (3) depends strongly upon how well the system operates. Almost every thing in the cryogenic system becomes a safety issue with option 3. If the there are chronic problems with the cryocooler for instance, that will be serious safety issue because argon would be constantly vented.

Option(1) has a mixing system that is so reliable that even, as shown in Table 3, with major operational problems occur once every two weeks, we still have an ODH 0 classification. With option (1), for the mixing system to fail one of two series of events must occur. Either both mixing fans do not start at the same time or there is a power outage, and then diesel generator does not start and the the UPS does not work. The calculated probability of failure for the mixing system for option 1 is 9.3^(-8) failures/demand which converts to 1 failure of the ODH mixing system every 55,600,000 times it is needed to prevent an ODH problem.

Option (1) requires a very careful design of the mixing system. The required high reliability of the mixing system is feasible, especially using standard techniques for safety systems for dangerous industrial processes. There would be multiple ODH heads monitoring oxygen concentration, two heads in the mixing system and two on the floor of the Minos Hall. Flow switches would be installed in the ductwork to tell if the fans are working. A small PLC (programmable logic controller) could daily test the fans to make sure they work.

Option (2) easily achieves ODH class 0 classification because of the vent header going outdoors. Because of the vent header, operational problems do not becomes safety problems. Once installed, the vent header is in effect a passive safety device, all it has to do, to do its job, is exist. The safety review process will be easier with option (2) than with option (1). Option (1) will undergo much more safety scrutiny and will have a greater engineering effort.

Some of the aspects of Option 1 design can be used with option 2. We may want to buy two fans so as to have one as a spare. The fan will be a critical component. Both fans could be installed although the analysis assumes one fan. A small UPS could be used so that the mixing fan will keep running between the time of a power outage and before the diesel generator starts.